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A modified Lemaitre damage model phenomenologically accounting for the Lode angle effect on ductile fracture

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Abstract

Dual phase (DP) steels consisting of two phases, ferrite and dispersed martensite, offer an attractive combination of strength and stretchability, which is a result of the strong distinctions of these constituents in mechanical properties. To properly describe the new features of these steels, various phenomenological uncoupled models or criteria are proposed in the past decade. These models or criteria determine more accurately the ductile fracture dependency on stress states in terms of stress triaxiality and Lode angle. However, they miss the softening effect caused by damage for materials in which damage is very much pronounced during large plastic deformation. In this study, a conventional Lemaitre damage model with isotropic hardening is adopted and modified in a phenomenological way to account for the Lode angle effect on ductile fracture. To demonstrate the necessity of incorporating the damage effect to stress-strain response, interrupted tests are performed to examine the damage evolution history. Notched dog-bone specimens with different radii are subsequently tested under the tensile loading to calibrate the material parameters and validate the model after material parameter calibration. With only five independent damage material parameters, the proposed model achieved a good accuracy on the prediction of the force–displacement response of deformation from uniaxial tension to plane-strain tension. The prediction of the final ductile fracture is also in a good agreement with the experimental data, which is a considerable improvement from the conventional Lemaitre damage model.

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Keywords: Damage mechanism; Stress triaxiality; CDM models; Ductile failure criteria; Ductile failure criteria; DP steel.

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1. Introduction

In the application of the modern advanced high-strength steels, e.g. dual-phase (DP) steel, damage has become a pronounced factor for the failure analysis, especially in the automotive sheet industry (Tasan et al., 2010). Most of the uncoupled ductile damage modes are challenged by this feature due to neglecting the softening of materials introduced by progressive accumulation of damage. The recently proposed hybrid damage plasticity model (Lian et al., 2013), which modified the uncoupled Bai–Wierzbicki model (Bai and Wierzbicki, 2008) to a coupled damage mechanics model, has been successfully applied to a DP steel sheet, DP600. In addition to the good precision of the predictive capability, the model also tends to bring more material parameters, which is severely hindering the application of it to a general or industrial scale. The solution to this problem is basically two folds: reducing the number of material parameters of the phenomenological models by new formulations or predicting the parameters by micromechanical simulations on the microstructure level. This study presents the development of a modified Lemaitre damage model in the application of the modelling of ductile fracture of DP600. The conventional Lemaitre damage model incorporates the softening effect caused by damage in the stress-strain response, whereas the predictive capability of the model in the low stress triaxiality and Lode angle regime is rather limited. To improve the predicative capacity of the Lemaitre damage model in more general stress states but still remain the low material parameter number, the effect of Lode angle effect on damage accumulation is phenomenologically introduced to the model in this study.

2. Constitutive equations

The starting point of the Lemaitre damage model is the definition of damage interval state variable D, which influences the plasticity behavior of the material and results the growth of interval voids and microcracks. Due to the effect of damage, the effective stress tensor $\tilde{\boldsymbol{\sigma}}$ and effective stress deviator $\tilde{\mathbf{s}}$ can be expressed as

$$\tilde{\boldsymbol{\sigma}} = \frac{\boldsymbol{\sigma}}{1 - D} \tag{1}$$

$$\tilde{\mathbf{s}} = \frac{\mathbf{s}}{1 - D} \tag{2}$$

where $\boldsymbol{\sigma}$ and $\mathbf{s}$ are the stress tensor and stress deviator for the damaged material. In terms of stress deviator, $\mathbf{s}$, and the hydrostatic pressure, $p \equiv 1/3\, tr[\boldsymbol{\sigma}]$, the damage elasticity law is applied as following:

$$\mathbf{s} = (1 - D)2G\boldsymbol{\varepsilon}_{\mathrm{d}}^{\mathrm{e}}; \quad p = (1 - D)K\,\varepsilon_{\mathrm{v}}^{\mathrm{e}} \tag{3}$$

where G and K are, respectively, the shear modulus and bulk modulus of the material; $\boldsymbol{\varepsilon}_{\mathrm{d}}^{\mathrm{e}}$ and $\varepsilon_{\mathrm{v}}^{\mathrm{e}}$ are the elastic strain deviator components and the elastic volumetric strain. Therefore, considering that the damage variable D is only effective during plastic deformation, the corresponding yield function and the associated flow rule is defined by

$$\Phi = \frac{\bar{\sigma}}{1 - D} - \sigma_{\mathrm{y}}\left(\bar{\varepsilon}^{\mathrm{p}}\right) \tag{4}$$

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}} = \dot{\gamma}\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} = \dot{\gamma}\frac{\mathbf{N}}{1 - D} \tag{5}$$

where $\overline{\sigma}$ is the equivalent stress, $\overline{\varepsilon}^{\mathrm{p}}$ is the equivalent plastic strain and $\sigma_{\mathrm{y}}(\overline{\varepsilon}^{\mathrm{p}})$ is the flow curve of the undamaged material; $\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}$ represents the plastic strain rate and $\dot{\gamma}$ is the plastic multiplier, which is subjected to the so-called Kuhn-Tucker conditions for the loading and unloading as

$$\dot{\gamma} \geq 0, \quad \Phi \leq 0, \quad \dot{\gamma}\Phi = 0 \tag{6}$$

N is the plastic flow direction tensor given by

$$\mathbf{N} = \frac{\partial \overline{\sigma}}{\partial \boldsymbol{\sigma}} = \frac{3}{2}\frac{\mathbf{s}}{\overline{\sigma}} \tag{7}$$

In conventional Lemaitre damage model, the increment of damage variable $\dot{D}$ is developed from the thermodynamic theory and accumulated mainly based on equivalent plastic strain rate $\dot{\gamma}$ and the damage strain release rate Y

$$\dot{D} = \dot{\gamma}\frac{1}{1-D}\left(\frac{-Y}{r}\right)^{s} \tag{8}$$

where r and S are the material parameters, and Y is defined by

$$-Y = \frac{\overline{\sigma}}{2E(1-D)^{2}}\left[\frac{2}{3}(1-\nu) + 3(1-2\nu)\left(\frac{p}{\overline{\sigma}}\right)\right] \tag{9}$$

in which E and ν are, respectively, the Young's modulus and Poisson ratio of the undamaged material.

From the above equation, the term $p/\overline{\sigma}$, referred to as stress triaxiality, is used in the definition of damage strain release rate Y, which introduces the influence of stress triaxiality to damage in the model. However, for another essential factor, the Lode parameter, is not considered in this conventional Lemaitre model, which leads to inaccurate prediction in complex stress states. In order to remediate this shortage, we propose an addition of a Lode parameter sensitivity function, initially used in the Xue–Wierzbicki (Xue, 2007) damage model to Eq. (8), to include the effect of Lode parameter. The Lode parameter sensitivity function is defined by

$$\mu(\theta_{L}) = \gamma + (1-\gamma)\left(\frac{\theta_{L}}{\pi/6}\right)^{k} \tag{10}$$

where γ is non-negative material constant and k is a shape parameter of the Lode parameter sensitivity function. Lode parameter θ_{L} is defined by

$$\sin 3\theta_{L} = -\frac{3\sqrt{3}}{2}\frac{J_{3}}{J_{2}^{3/2}} \tag{11}$$

With this equation, Eq. (8) is rewritten as

$$\dot{D} = \frac{\dot{\gamma}}{\mu(\theta_{L})}\frac{1}{1-D}\left(\frac{-Y}{r}\right)^{s} \tag{12}$$

in which a phenomenological Lode effect is simply added to the original Lemaitre damage model. The model is, therefore, referred to as the phenomenologically Lode angle effect added (PLA) Lemaitre damage model. In addition, the ductile fracture is assumed to occur, when the damage is accumulated to a critical value, D_{cr}. The model is implemented into Abaqus/Explicit by a user defined subroutine, VUMAT. Due to the space limitation, the implementation algorithm is not detailed in this paper.

3. Experimental and numerical procedures

To illustrate the significance of damage, interrupted tests of notched dog-bone specimens in cooperation with the subsequent microscope investigation were performed and it is concluded that the damage is a main factor to cause the softening of DP600. In order to calibrate the five material parameters in the PLA-Lemaitre damage model and validate the model under different stress states, a series of flat notched dog-bone specimens with various notch radii are designed to achieve the different stress states. The basic geometry of the notched dog-bone specimen is based on the standard smooth specimen geometry in DIN50114. Upon that, radii of 80mm, 20mm, 10mm, 5mm and 2mm are attached to gain the different stress triaxialities and Lode angles in the central cross-section of the specimen. The sketch of specimen geometry is shown in Fig. 1.

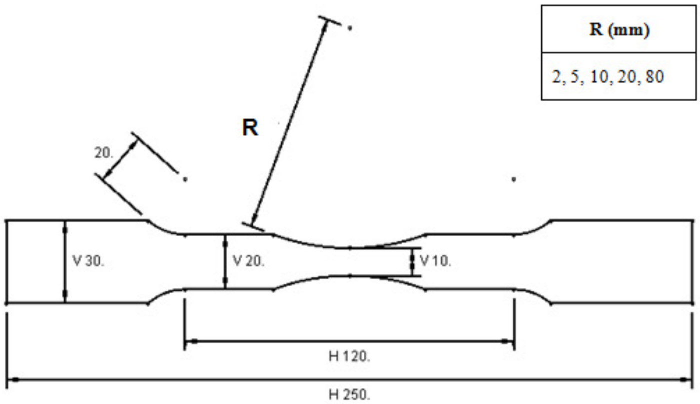


Fig. 1. Geometries and dimensions of the notched dog-bone tensile specimens.

In this design, the stress state of the specimen with notch radius 80mm is close to uniaxial tension. On the contrary, the stress state of the specimen with notch radius 2mm is similar to plane-strain tension. The stress states of the other three specimens with notch radii of 20mm, 10mm and 5mm are distributed between uniaxial tension and plane-strain tension. The gauge length of the specimen is 80mm and the cross-head speed is 0.2 mm/min. The finite element (FE) models are built in Abaqus/Explicit based on the measured geometries of tested specimens, as shown in Fig. 2.

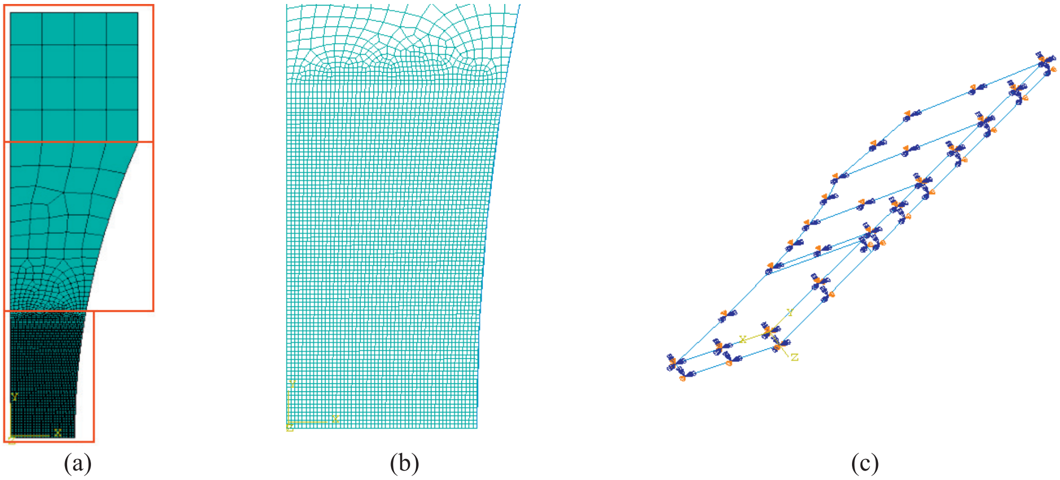
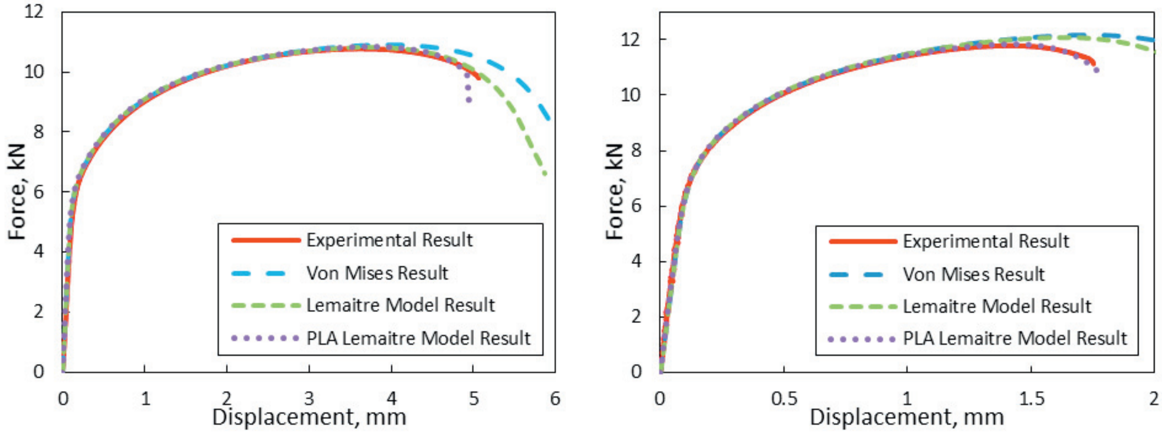


Fig. 2. Mesh and boundary conditions of the notched dog-bone specimen: (a) three partitioned mesh zones; (b) critical mesh zone; (c) boundary conditions set-up.

The models are developed in 1/8 size of the full specimens in order to reduce the total amount of elements and save the calculation time. Therefore, symmetry boundary conditions are applied to the three symmetric planes of the model (shown in Fig. 2). The models are meshed by eight-node brick elements with reduced integration point (C3D8R) and each model is partitioned into critical zone, transitional zone and ineffective zone to mesh with different mesh sizes (shown in Fig. 2). The mesh size in critical zone is chosen as 0.1 mm × 0.1 mm × 0.1 mm in order to obtain the accurate prediction during the tests. The height of the critical zone for each models is designed individually, to ensure that the contour of the effective equivalent plastic strain (PEEQ) larger than 0.1 is always in the critical zone.

4. Results and discussion

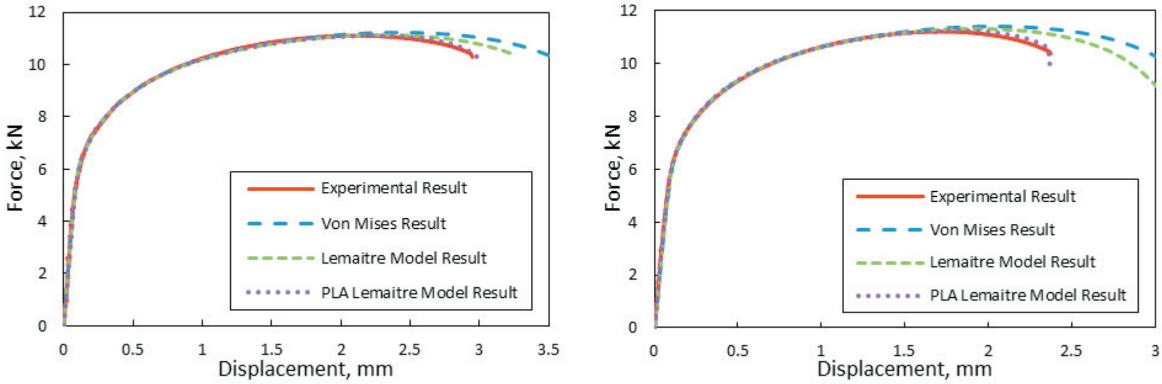
In this study, the damage parameter fitting is performed by an iterative procedure of evaluating the fitting goodness of the force–displacement response of the tensile test. The first step is to fit the material parameters of the original Lemaitre damage model, r and S. As the Lode effect function is not adding any influence to the damage accumulation under the uniaxial tension stress state, the PLA-Lemaitre damage model is reduced to the original Lemaitre damage model under uniaxial tension. Therefore, the specimen with notch radius of 80mm is used for the calibration. Normally, the parameter S is suggested to be one, so only the parameter r is fitted. As shown in Fig. 3 (a), compared to the elastoplastic von Mises plasticity model, the Lemaitre damage model is in a good agreement with the experiment when $r = 38$. After that, two Lode effect parameters are calibrated with R2 specimen. The detailed parametric study of these two parameters are not shown here due to the space limitation. As shown in Fig. 3 (b), the Lemaitre damage model with the parameter calibrated from R80 specimen obviously overestimates the experiment due to the lack of the Lode effect on the damage softening. With the selection of $\gamma = 4.0$ and $k = 0.2$, a good agreement is achieved for the R2 specimen. When it is applied to the R80 specimen, the predicted result is still in line with the experiment. Based on the average best fit of both R2 and R80 specimens, the critical damage variable value D_{cr} is fitted as 0.2 to control the element deletion for the ductile fracture.



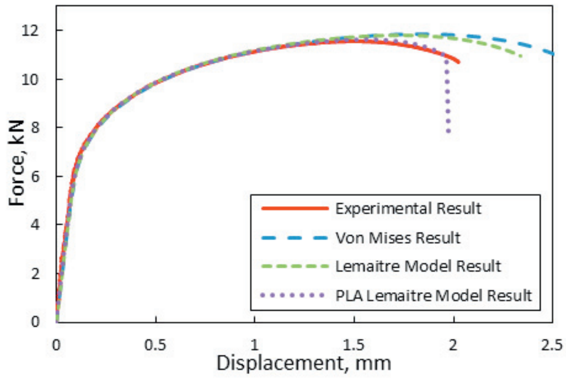
(a) (b)

Fig. 3. Comparison of the experimental and numerical results by von Mises plasticity model, Lemaitre damage model and PLA-Lemaitre damage model of notched dog-bone specimens with radius of 80 mm (a) and 2mm (b).

To examine the predictive capability of the model, the rest geometries of the notched dog-bone specimens are simulated with the calibrated set of parameters to compare the force–displacement curves with the experimental results, as shown in Fig. 4. In these results, the von Mises plasticity model overestimates the force–displacement responses for all geometries, in particular after the maximum force as it is not considering the damage procedure after necking. However, it is a good marker to compare the performance of other two models. The Lemaitre damage model without considering the Lode effect improves the prediction, but the softening effect is still not sufficient. PLA-Lemaitre damage model gives a good prediction for all three specimens in terms of the force–displacement response as well as the final ductile fracture.



(a) (b)



(c)

Fig. 4. Comparison of the experimental and numerical results by von Mises plasticity model, Lemaitre damage model and PLA-Lemaitre damage model of notched dog-bone specimens with radius of 20 mm (a), 10mm (b) and 5mm (c).

5. Conclusions

The paper presents the development of a modified Lemaitre damage model, PLA-Lemaitre damage model. By phenomenologically adding the Lode angle effect to the damage accumulation, very good predicative accuracy is achieved in a broad range of the stress states. In addition, the number of the material parameters remains low and the calibration procedure is also rather straightforward.

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